

Determining SUSY and Higgs Parameters in the MSSM and its Extensions

SEONG YOUL CHOI

Department of Physics, Chonbuk National University, Chonju 561-756, Korea

E-mail: sychoi@chonbuk.ac.kr

ABSTRACT

If supersymmetry (SUSY) is realized at the electroweak scale, its underlying structure and breaking mechanism may be explored with great precision by a future linear e^+e^- collider (LC) with a clean environment, tunable collision energy, high luminosity polarized beams, and additional e^-e^- , $e\gamma$ and $\gamma\gamma$ modes. We review a few recent developments for determining fundamental SUSY and Higgs parameters, measuring CP violating H/A mixing in the decoupling regime and probing the next-to-minimal supersymmetric standard model at the LC.

1. Introduction

Weak-scale SUSY has its natural solution to the gauge hierarchy problem, providing a stable bridge between the electroweak scale and the grand unification or Planck scale, with which the roots of standard particle physics are expected to go as deep as the Planck length of 10^{-33} cm. It is then crucial to probe SUSY and its breaking with great precision at a future e^+e^- linear collider (LC) [1] as well as the large hadron collider (LHC) [2] for a reliable grand extrapolation to the Planck scale [3].

In this talk we review a few recent developments for determining fundamental SUSY and Higgs parameters, measuring CP violating H/A mixing in the decoupling regime and probing the next-to-minimal supersymmetric standard model (NMSSM) at the LC.

2. A new $\tan\beta$ determination method: $\tau\tau$ fusion to SUSY Higgs bosons

For large pseudoscalar Higgs mass the heavy H/A Higgs couplings to down-type fermions are directly proportional to $\tan\beta$ if the parameter is large so that they are highly sensitive to its value [4]. Also the down-type couplings of the light h Higgs boson in the MSSM are close to $\tan\beta$ if M_A is moderately small. Based on these observations, we show that $\tau\tau$ fusion to Higgs bosons at a photon collider [5] can provide a valuable method for measuring $\tan\beta$, after searching for Higgs bosons in $\gamma\gamma$ fusion [6].

For large $\tan\beta$, all the Higgs bosons Φ ($= H, A, h$) decay almost exclusively [80 to 90%] to a pair of b quarks so that the final state consists of a pair of τ 's and a pair of resonant b quark jets. Two main background processes - the $\tau^+\tau^-$ annihilation into a pair of b -quarks via s -channel γ/Z exchanges and the diffractive $\gamma\gamma \rightarrow (\tau^+\tau^-)(b\bar{b})$ events with the pairs scattering off each other by Rutherford photon exchange - can be suppressed strongly by choosing proper cuts [5].

The left panel of Fig. 1 shows the exact cross sections for the signals of H and A Higgs-boson production in the $\tau\tau$ fusion process with $E_{\gamma\gamma} = 600$ GeV, together with all the background processes with appropriate experimental cuts. As shown in the right

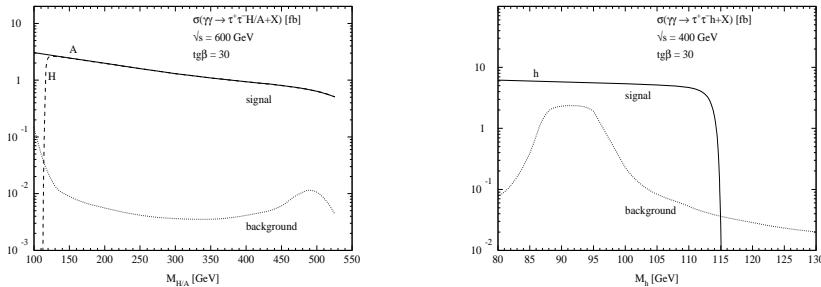


Figure 1: The cross sections for the production of the H/A (left) and h (right) Higgs bosons in the $\tau\tau$ fusion process at a $\gamma\gamma$ collider for $\tan\beta = 30$. Also shown is the background cross section with experimental cuts. \sqrt{s} denotes the $\gamma\gamma$ collider c.m. energy.

panel of Fig. 1 $\tau\tau$ fusion to the light Higgs boson h with $E_{\gamma\gamma} = 400$ GeV can also be exploited to measure large $\tan\beta$ for moderately small M_A . For h production, the mass parameters are set to $M_A \sim 100$ GeV and $M_h = 100$ GeV. The channels h/A and H/A are combined in the overlapping mass ranges in which the respective two states cannot be discriminated. Since in the region of interest the $\tau\tau$ fusion cross sections are proportional to $\tan^2\beta$ and the background is small, the absolute errors $\Delta \tan\beta$ are nearly independent of $\tan\beta$, varying between ~ 0.9 and 1.3 for Higgs masses away from the kinematical limits for the integrated luminosity of $200/100 \text{ fb}^{-1}$ for the high/low energy option.

3. Probing Majorana nature and CP violation in the neutralino system

Once several neutralino candidates are observed it will be crucial to establish the Majorana nature and CP properties of neutralinos as well as to reconstruct the fundamental SUSY parameters at the LC [7]. In this report, we present two powerful methods for probing the Majorana nature and CP violation in the neutralino system.

When the electron/fermion masses are neglected both the production processes, $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$, near threshold and the three-body decays, $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 f \bar{f}$, near the fermion invariant mass end point are effectively regarded as processes of a static (axial-)vector current exchange between two neutralinos. In the CP invariant case, the neutralino $\{ij\}$ pair production and the decay $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 V$ through a vector current satisfy the CP relations

$$1 = \pm \eta^i \eta^j (-1)^L \quad (1)$$

for static neutralinos, with $\eta^i = \pm i$ the intrinsic $\tilde{\chi}_i^0$ CP parity and L the orbital angular momentum of the produced pair $\{ij\}$ and of the final state of $\tilde{\chi}_j^0$ and V , respectively. Therefore, in the CP invariant case, if the production of a pair of neutralinos with the same (opposite) CP parity is excited slowly in P waves (steeply in S waves), then the neutralino to neutralino transition is excited sharply in S waves (slowly in P waves).

In the CP noninvariant case the orbital angular momentum is no longer restricted by the selection rules (1). Consequently, CP violation in the neutralino system can clearly be signalled by (a) the sharp S -wave excitations of the production of three non-diagonal $\{ij\}$, $\{ik\}$ and $\{jk\}$ pairs near threshold [7,8] or by (b) the simultaneous S -wave excitations of

the production of any non-diagonal $\{ij\}$ pair in e^+e^- annihilation near threshold and of the fermion invariant mass distribution of the neutralino three-body decays $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 f \bar{f}$ near the kinematical end point [9]. Note that even the combined analysis of the production of the lighter neutralino $\{12\}$ pair and the associated decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 f \bar{f}$ enables us to probe CP violation in the neutralino system.

Once two-body neutralino decays are open, the combined production-decay analysis cannot be exploited for probing CP violation in the neutralino system. Nevertheless, if the two-body decays $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_j^0 Z$ is not too strongly suppressed, the Z polarization reconstructed via leptonic Z -boson decays with great precision allows us to probe the Majorana nature and CP violation in the neutralino system [10].

4. Resonant CP violating H/A mixing in the decoupling regime

With non-vanishing CP phases in the soft SUSY-breaking terms in the MSSM, radiative corrections induce two CP-even Higgs bosons, h and H , and one CP-odd Higgs boson, A , to mix forming a triplet (H_1, H_2, H_3) without definite CP parities [11]. The H/A mixing can be large in the limit with heavy and nearly-degenerate H and A . The lightest Higgs H_1 then becomes the SM-like Higgs, and does not mix with the H/A system.

For small mass differences, the mixing is strongly affected by the widths of the states and the complex, symmetric Weisskopf-Wigner mass matrix $\mathcal{M}_c^2 = M^2 - iM\Gamma$ must be considered in total, not only the real part. Recently a coupled-channel method has been employed [12] for the Higgs formation and decay processes at the LHC. We have presented an alternative approach in Ref.[13] where the full mass matrix \mathcal{M}_c^2 is diagonalized by a complex rotation matrix. For the H/A system, the 2×2 rotation matrix is expressed in terms of a *complex* mixing angle θ , satisfying

$$X = (1/2) \tan 2\theta = \mathcal{M}_{HA}^2 / (\mathcal{M}_{HH}^2 - \mathcal{M}_{AA}^2) \quad (2)$$

where \mathcal{M}_{HA}^2 and $\mathcal{M}_{HH,AA}^2$ are the off-diagonal and diagonal entries of the matrix \mathcal{M}_c^2 .

The complex H/A mixing is shown in the left panel of Fig. 2 for $M_S=0.5$ TeV, $|A_t|=1$ TeV, and $\mu=1$ TeV, $\tan \beta=5$, while varying the phase ϕ_A of the trilinear parameter A_t .

A photon linear collider would be an ideal tool to study resonant CP violation in the Higgs sector. Two promising signatures have been considered in Ref.[13]. For linearly polarized photons, the CP-even (CP-odd) component of the H_i wave-functions is projected out if the polarization vectors are parallel (perpendicular), respectively. This can be observed in the CP-even asymmetry \mathcal{A}_{lin} , since $|\mathcal{A}_{lin}| < 1$ requires both scalar and pseudoscalar $\gamma\gamma H_i$ non-zero couplings. Moreover, CP violation due to H/A mixing can directly be probed via the CP-odd asymmetry \mathcal{A}_{hel} constructed with circular photon polarization. In addition, correlations between the transverse t and \bar{t} polarization vectors s_\perp, \bar{s}_\perp in the decay process $H_i \rightarrow t\bar{t}$, lead to a non-trivial CP-even correlation $\mathcal{C}_\parallel = \langle s_\perp \cdot \bar{s}_\perp \rangle$ and a CP-odd azimuthal correlation $\mathcal{C}_\perp = \langle \hat{p}_t \cdot (s_\perp \times \bar{s}_\perp) \rangle$.

The middle panel of Fig. 2 shows the asymmetries \mathcal{A}_{lin} (solid line) and \mathcal{A}_{hel} (dashed line) in the $\gamma\gamma$ collider as the $\gamma\gamma$ energy is scanned from below M_{H_3} to above M_{H_2} . The right panel shows the $E_{t\bar{t}}$ dependence of the correlators \mathcal{C}_\parallel (solid line) and \mathcal{C}_\perp (dashed

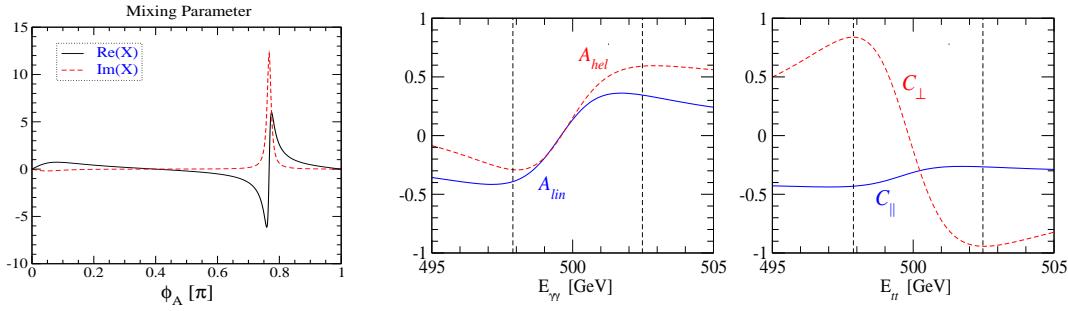


Figure 2: Left: The ϕ_A dependence of the parameter X (left). Middle: The $E_{\gamma\gamma}$ dependence of $\mathcal{A}_{lin,hel}$ in the process $\gamma\gamma \rightarrow H_i$. Right: The $E_{t\bar{t}}$ dependence of $\mathcal{C}_{\parallel,\perp}$ in the production–decay chain $\gamma\gamma \rightarrow H_i \rightarrow t\bar{t}$. In the middle and right figures $\phi_A = 3\pi/4$. The vertical lines represent the two mass eigenstates.

line) for $\phi_A = 3\pi/4$, a phase value close to resonant CP mixing. Detailed experimental simulations would be needed to estimate the accuracy with which they can be measured. However, the large magnitude and the rapid, significant variation of the asymmetries through the resonance region would be a very interesting effect to observe in any case.

5. Neutralino sector in the next-to-minimal supersymmetric standard model

The NMSSM superpotential [14,15] with an iso-singlet Higgs superfield \hat{S} in addition to the two Higgs doublets superfields $\hat{H}_{u,d}$ is given by

$$W = W_Y + \lambda \hat{S} (\hat{H}_u \hat{H}_d) + \frac{1}{3} \kappa \hat{S}^3 \quad (3)$$

where W_Y denotes the usual MSSM Yukawa components. The two dimensionless parameters λ and κ are less than 0.7 and $\kappa \lesssim \lambda$ is favored at the electroweak scale if they remain weakly interacting up to the GUT scale [14].

The singlet superfield adds an extra higgsino to the MSSM neutralino spectrum, called a *singlino*, resulting in five neutralinos. We denote the singlino dominated neutralino $\tilde{\chi}_5^0$, with $\tilde{\chi}_{1-4}^0$ denoting the other four neutralinos in order of ascending mass. The neutralino spectrum for an example scenario is shown in Fig. 3 (left) as a function of $\mu_\lambda \equiv \lambda v / \sqrt{2}$.

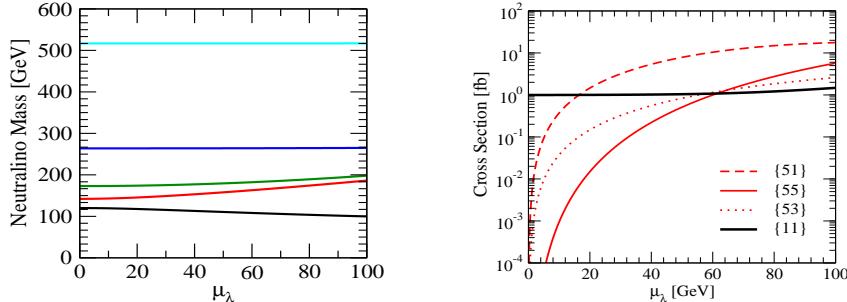


Figure 3: The neutralino mass spectrum (left) and the cross-sections for $e^+e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$ at $\sqrt{s} = 500$ GeV (right) as a function of μ_λ , for $\mu_\kappa = 120$ GeV, $\mu = 170$ GeV, $\tan \beta = 3$, $M_{1,2} = 250/500$ GeV.

In this scenario, the singlino dominated neutralino (black) is the lightest neutralino

(and the LSP) with a mass of approximately $\mu_\kappa \equiv 2\kappa\langle S \rangle$ so that it will be copiously produced at the LHC in squark and gluino cascade decays. A very decoupled state with low λ can give rise to macroscopic flight distances of order a μm and order a nm for the decays $\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_5^0 l^+ l^-$ and $\tilde{l}_R \rightarrow \tilde{\chi}_5^0 l$ with $\mu_\lambda = 1 \text{ GeV}$, respectively. Also shown in Fig. 3 (right) are the cross sections for $e^+ e^- \rightarrow \tilde{\chi}_i^0 \tilde{\chi}_j^0$, for production of singlino-like ($\tilde{\chi}_5^0$), gaugino-like ($\tilde{\chi}_1^0$) and higgsino-like ($\tilde{\chi}_3^0$) neutralinos. With the integrated luminosity of 1 ab^{-1} , large event rates of order 10^3 are expected unless μ_λ is too small.

For $\kappa \gtrsim \lambda/2$, the singlino $\tilde{\chi}_5^0$ is no longer the LSP and it can decay to $\tilde{\chi}_1^0$. Such a neutralino sector would be very difficult to distinguish from that of the MSSM.

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